LEAP and TEM of AlGaN/GaN HEMTs

Ray Holzworth, Patrick Whiting, and
Dr. Kevin S. Jones

GATOR Engineering
UNIVERSITY OF FLORIDA

Outline

- Materials we use
- What is LEAP?
- Summary from last review
- Tool Development
  - LEAP
- Devices
  - AFRL Device Study
  - MIT Collaboration with del Alamo
  - Importance of Zone Axis
- Blanket Wafers
  - Bending Experiment
    - Set up
    - Samples
    - Preliminary results
- Future Work

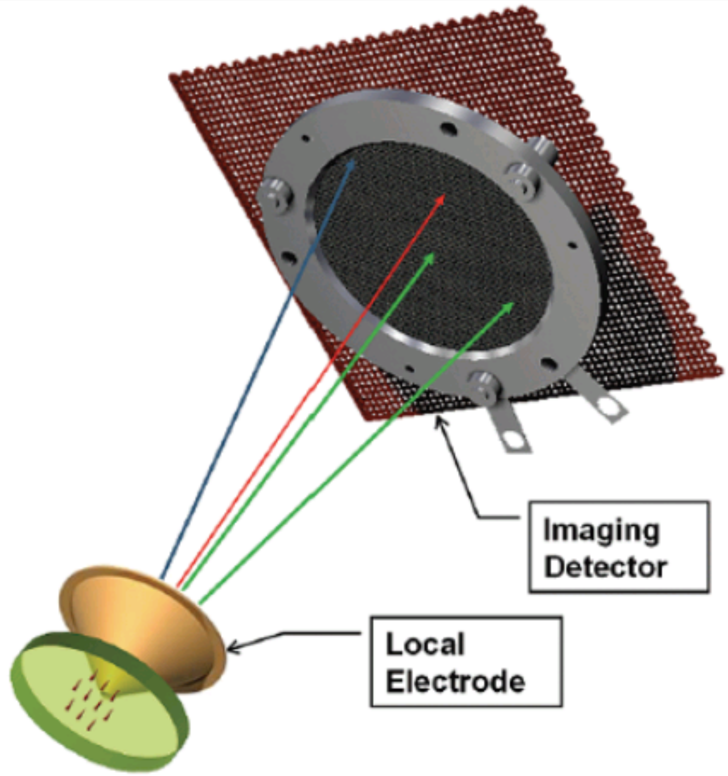
What materials do we use?

- Devices (Nitronex, AFRL, MIT)
  - Analyze defects
  - Develop analysis techniques
    - LEAP
      - Determine composition and structure to establish the correlation between structure, properties and failure

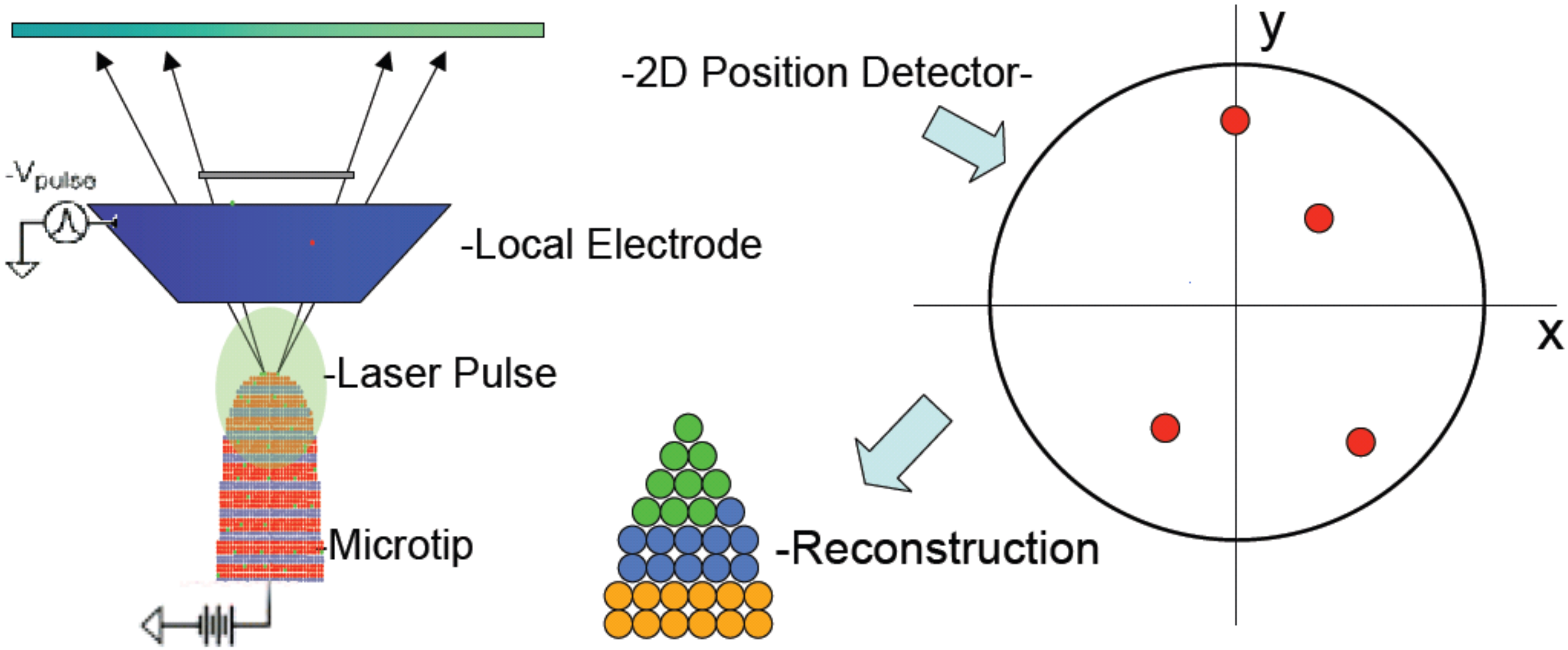
- Blanket Wafers (Nitronex epi-layer)
  - Isolate parameters that affect device reliability
    - Stress
    - Temperature
    - Composition

What is LEAP?

Local Electrode Atom Probe



How LEAP Works



Data collected:

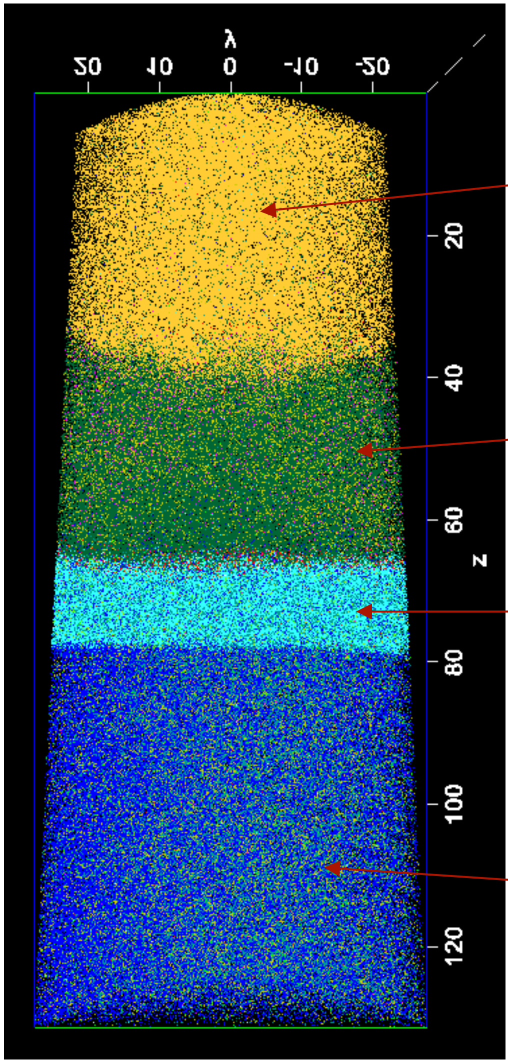
- (x,y) position of impact on detector
- Impact sequence number
- Time of flight

Resulting analysis:

- (x,y) position of atom in plane of the tip
- Position of atom along z-axis
- Element identification

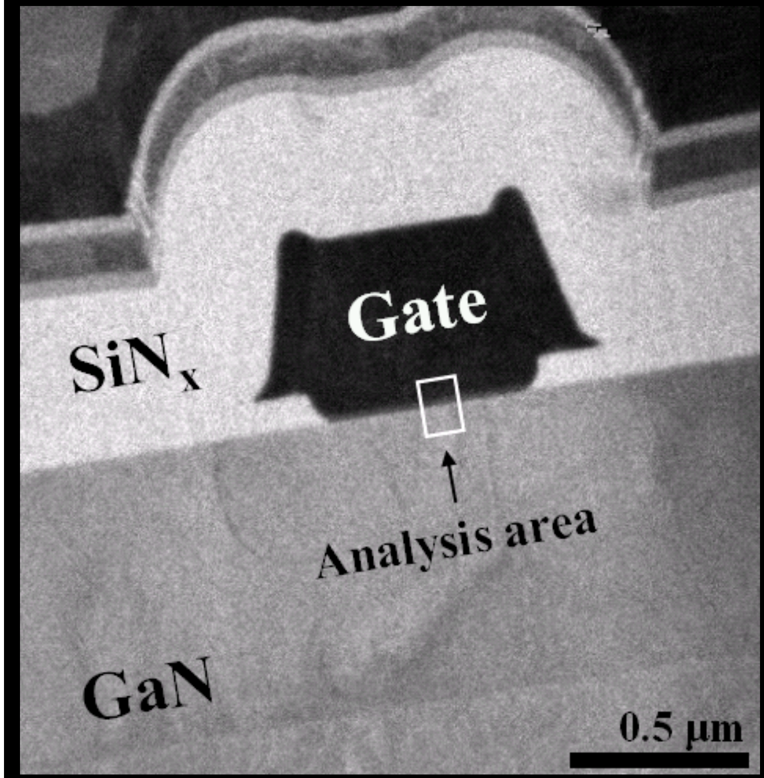
Last Review: LEAP of gate stack and AlGaN/GaN epilayers

- LEAP reconstruction of gate region (Nitronex)
  - Gate metal stack
  - Gate/Semiconductor interface
  - AlGaN/GaN interface

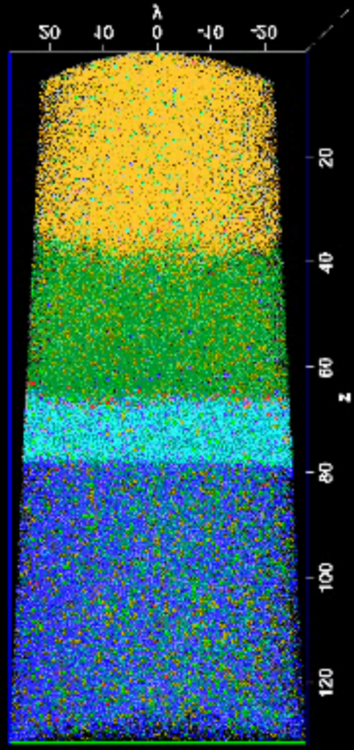


Last Review: LEAP Reconstruction (Nitronex)

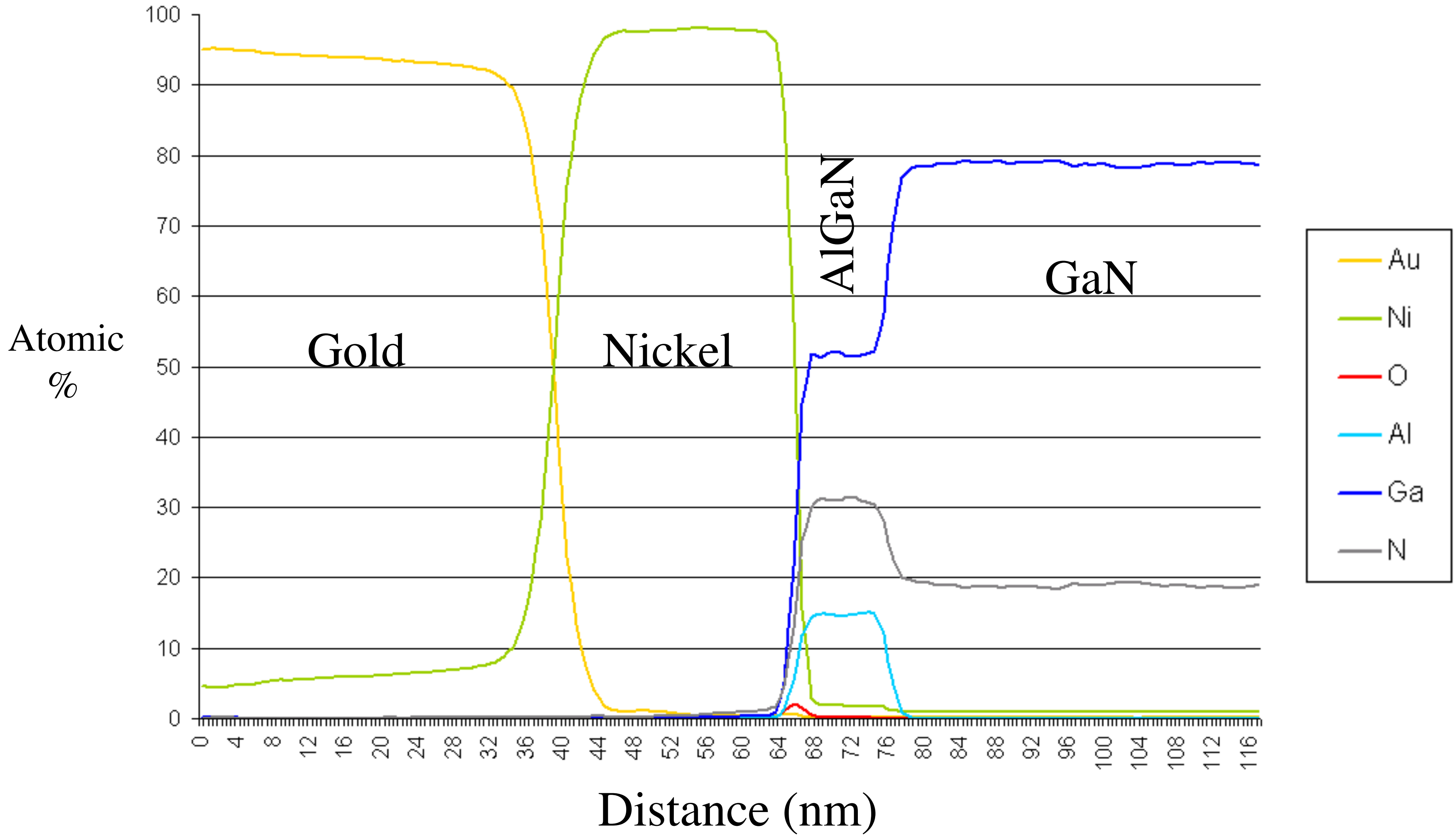
- TEM



- LEAP



Last Review: 1-D Concentration Profile (Nitronex)



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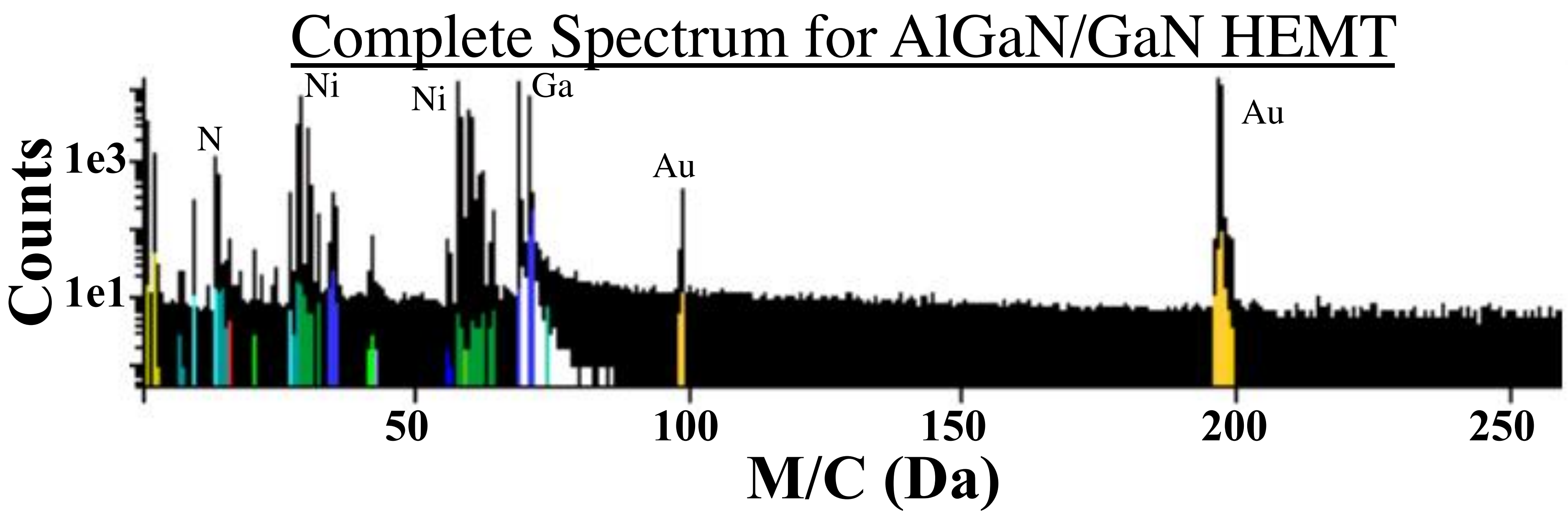
Mass-to-Charge (M/C) Spectrum for Device

- Not as straight forward/simple as expected
  - Peak Overlap
  - Ion Ratios
- While a priori knowledge of composition isn't necessary
  - It is very helpful



Peak Overlap Problems

- M/C overlap problems
  - Peaks from two different ions overlap each other

Examples:

- O_2^+ and isotope of doubly charged Ni (Ni-64^{++})
  - 32
- NiH^+ and AlO_2^+
  - 59
- N^+ and Si^{++} & Ni^{++} and Si^+
  - 14, 14.5, 15, 28 & 29, 30
- All limit accuracy of compositional analysis at the gate/semiconductor interface which is where the structure needs to be known

How to Identify Peak Overlaps?

- Ni^{++}-64 and O_2^+ both have a M/C = 32
  - How do we know there is an overlap issue?
    - Determine the species by comparing the isotopic nickel ratios

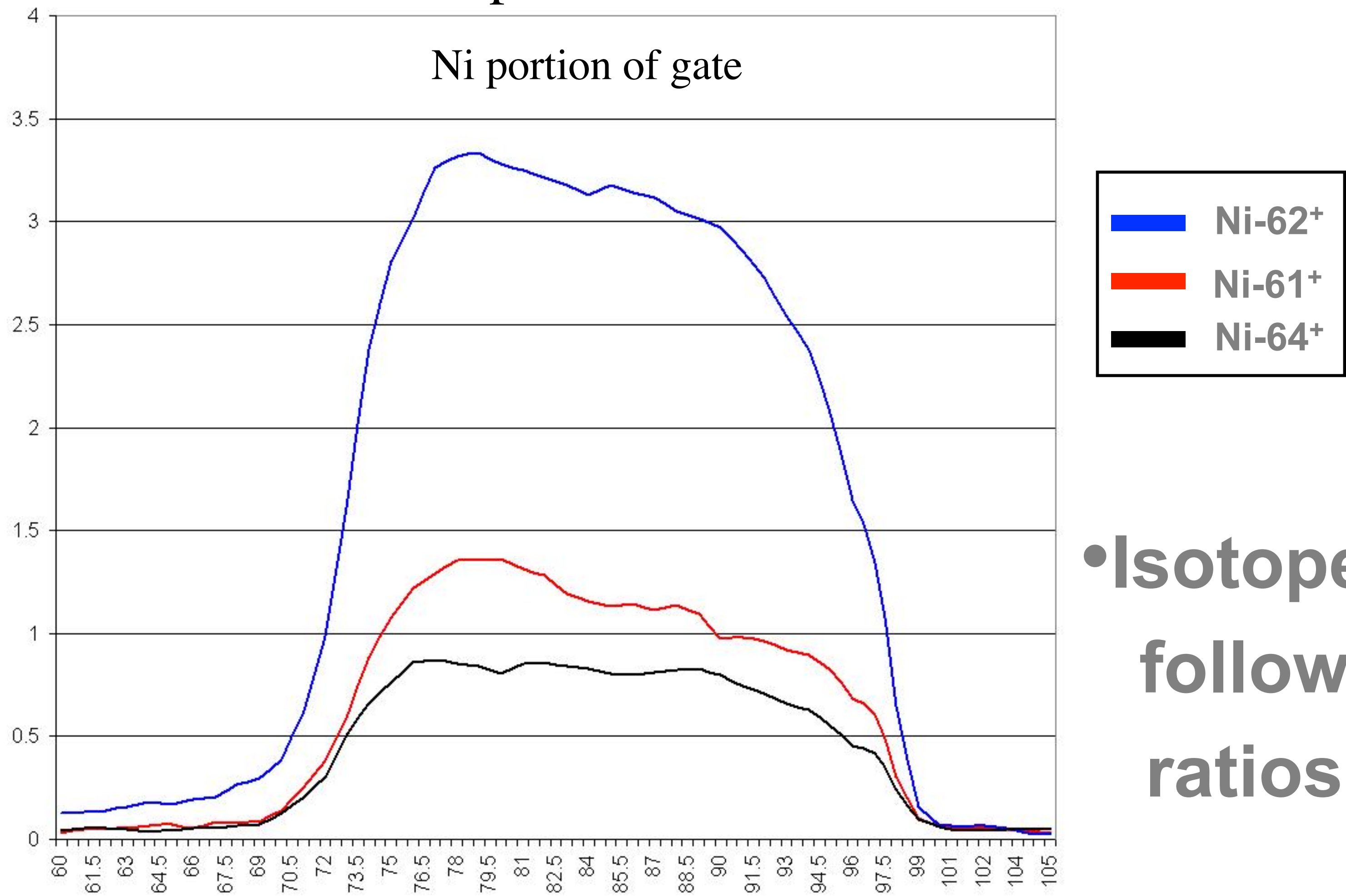
- Ni-58, 68.1%
- Ni-60, 26.2%
- Ni-61, 1.1%
- Ni-62, 3.6%
- Ni-64, 0.9%

Nickel composition should show that:
58 > 60 > 62 > 61 > 64

Gate Composition of Single Charged Ni Isotopes

1-D Composition Profile

Ionic %



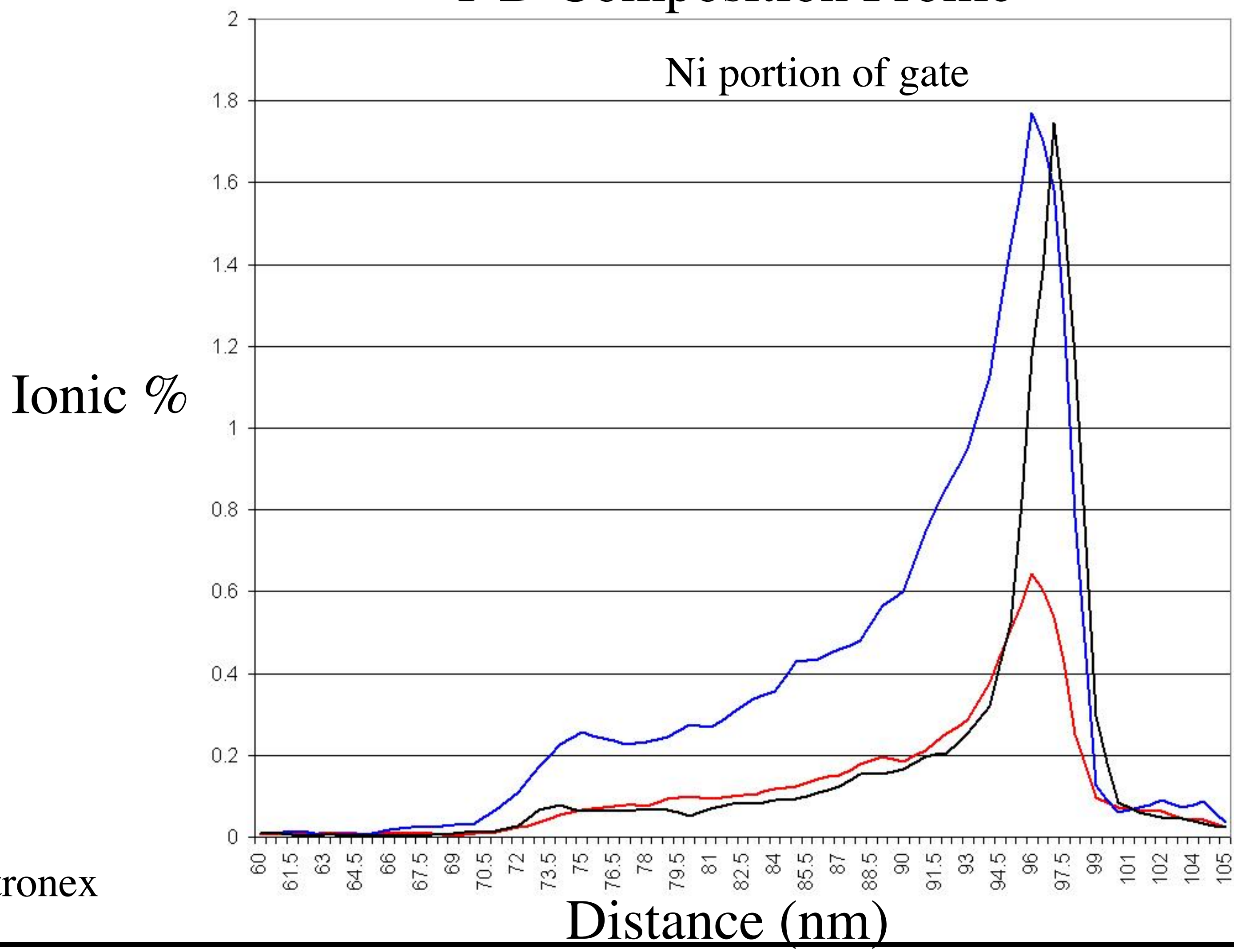
Distance (nm)

- **Isotopes follow ratios**

*Nitronex

Gate Composition of Doubly Charged Ni Isotopes

1-D Composition Profile



- **Isotopes DO NOT follow ratios**

=>32 isn't pure Ni^{++} peak

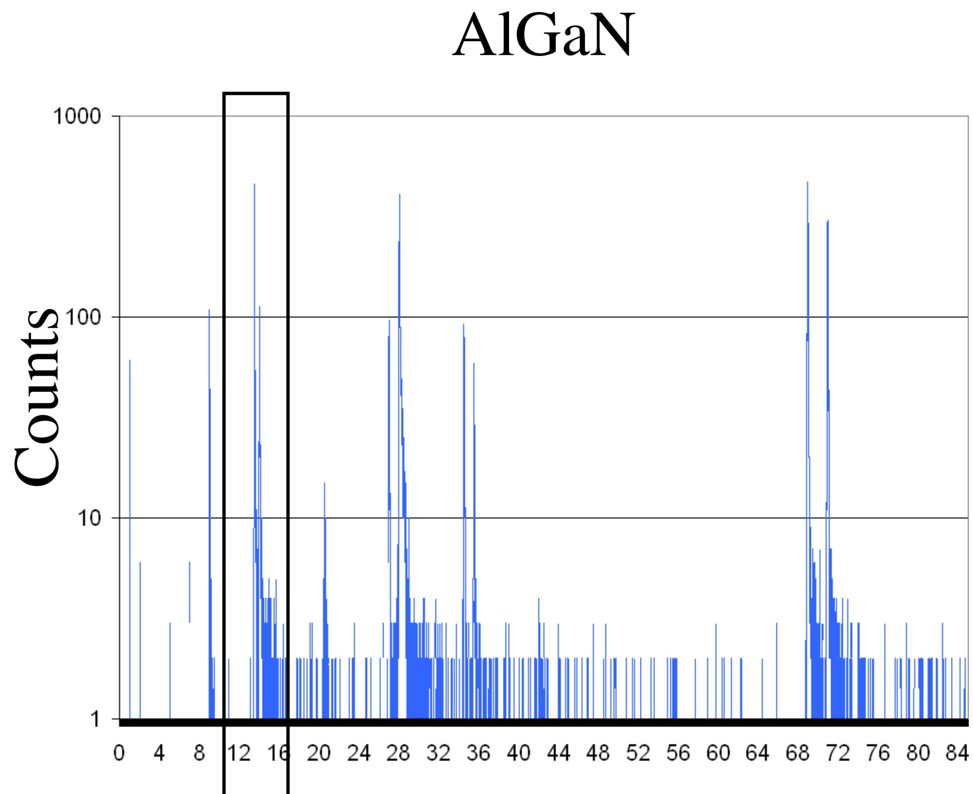
*Nitronex

Understanding the M/C-32 Peak

- Isotopic ratio is incorrect
  - Therefore, M/C-32 is composed of O_2^+ and Ni^{++}-64
- How can you separate the two possibilities?
  - Decompose peak using analysis software
    - Input possibilities for peak
    - Software uses theoretical isotopic ratios and compares them to ratios found in sample
    - Computes the percentage of peak from each possbility
- Decomposition of Peak
  - 61.2 % O_2^+
  - 38.8 % Ni^{++}-64

Ion Ratios

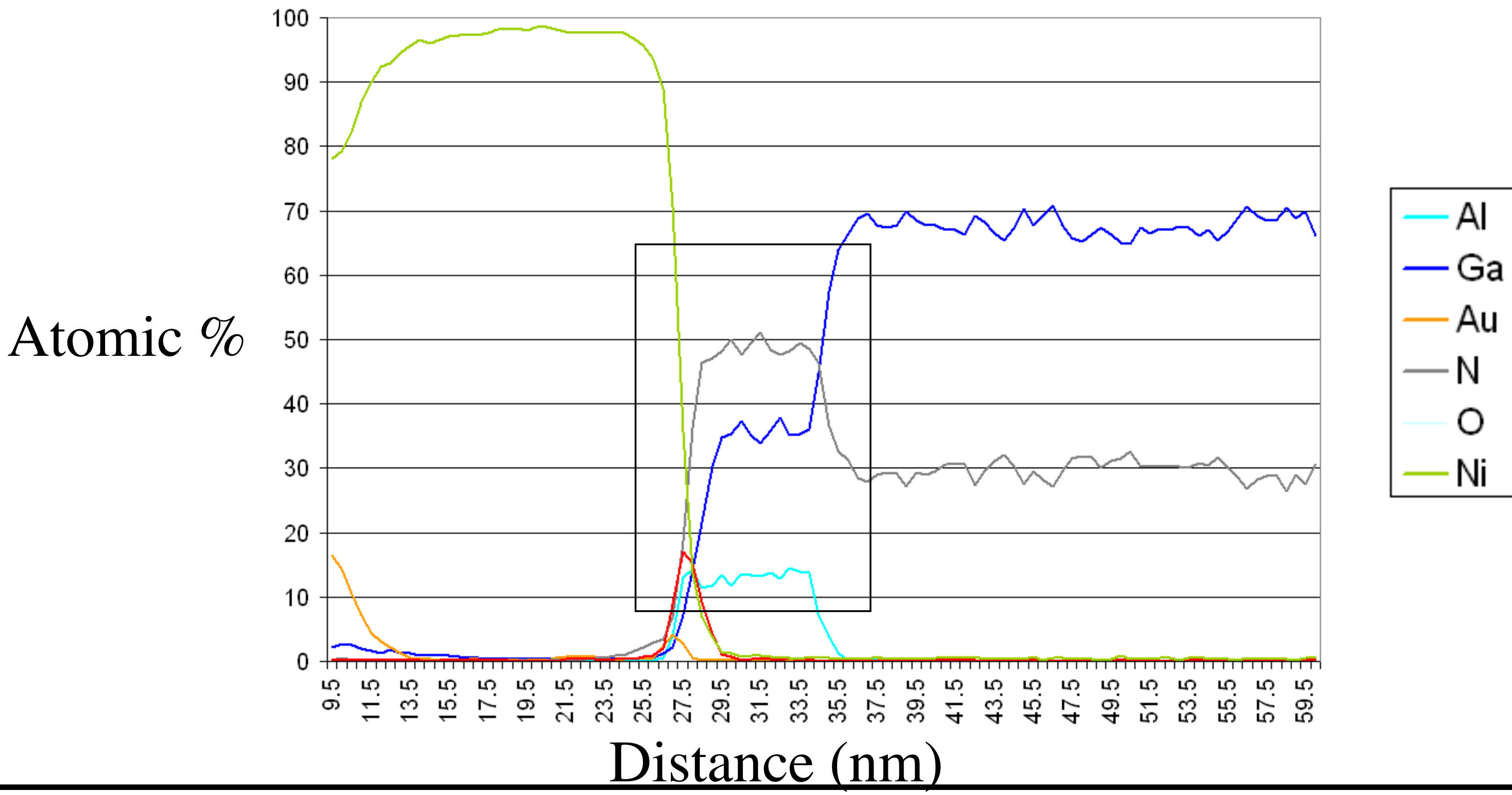
- Similar to the peak overlap problem except it involves the same ion with multiple charge states
  - Example
    - 14
      - N^+, N_2^{++}, etc.



*Nitronex

Updated 1-D Concentration Profile using Ion Ratios

- At M/C-14 it appears N_2^{++} is the major ion evaporating
  - Updating the 1-D concentration profile shows the AlGaN ratio has been corrected



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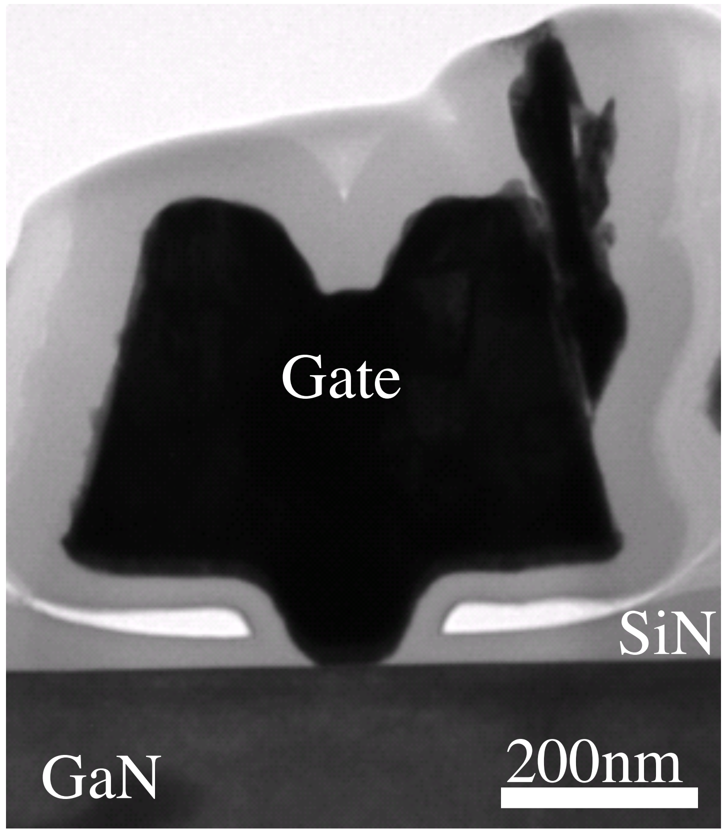
AFRL Device Study

- Devices are easily shared among the UF MURI groups
  - Internal device used with the MURI
    - Allows for uniform device material
  - Facilitates collaboration between groups
    - Groups are setup to use device

AFRL Device Study

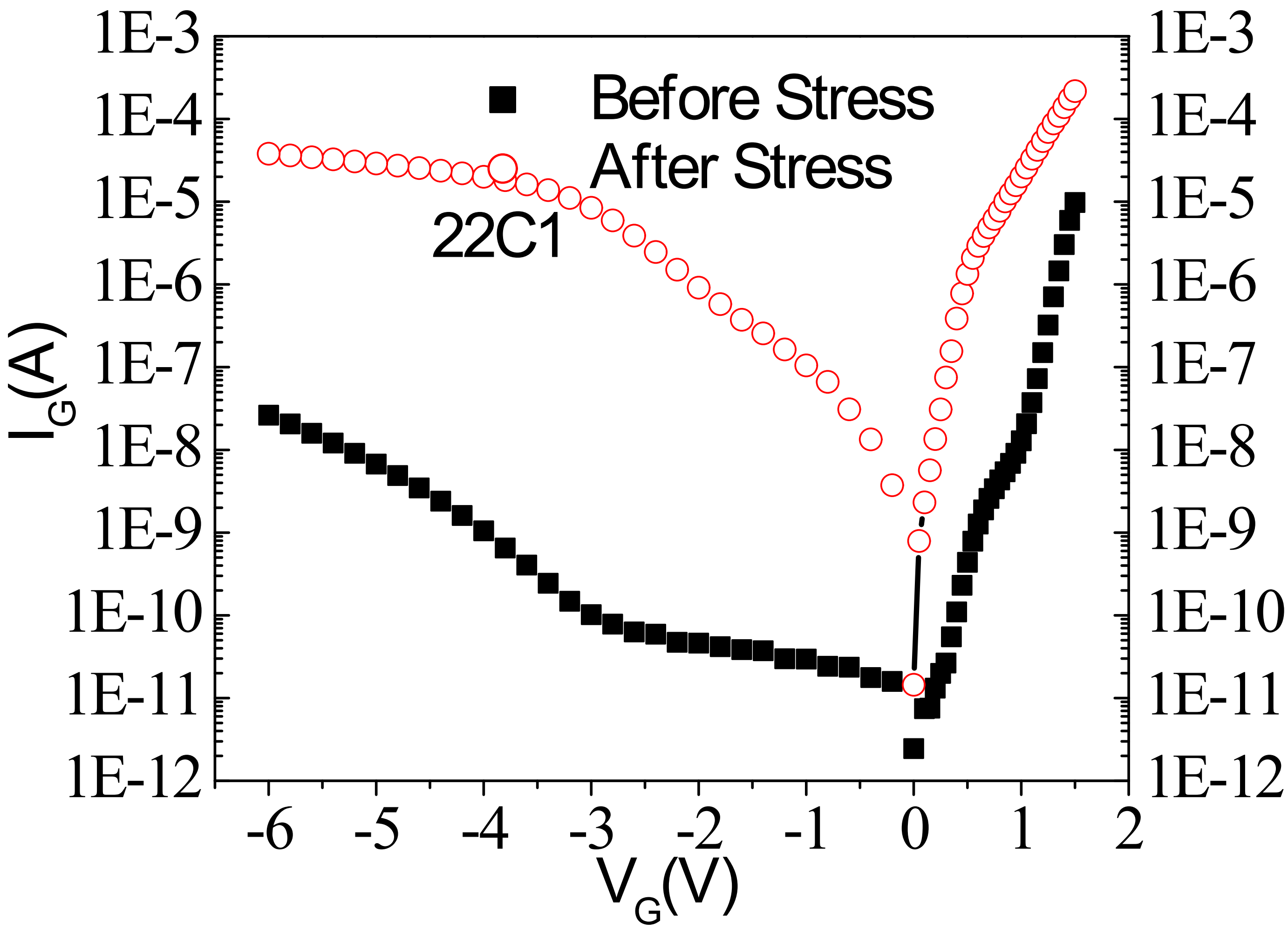
- XTEM of 100nm gate unstressed device



- V_{DS}= 10V while V_G was stepped from -10 to -42V by 1 min steps

AFRL Device Study

- IV Gate Curve



Stress Conditions

V_G = 10V

V_{DS} =-10V to -42V

- 1 min steps

AFRL Device Study

Stress Conditions

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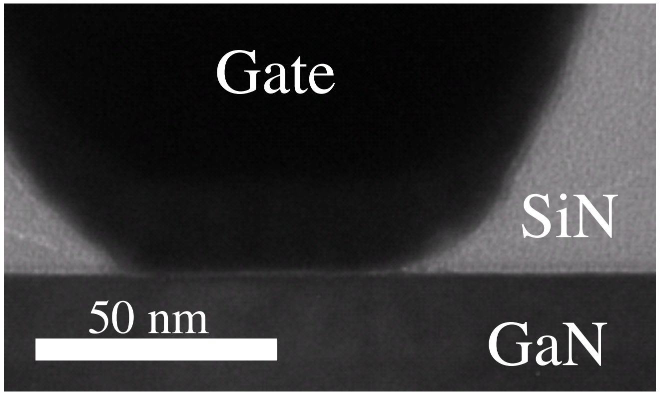
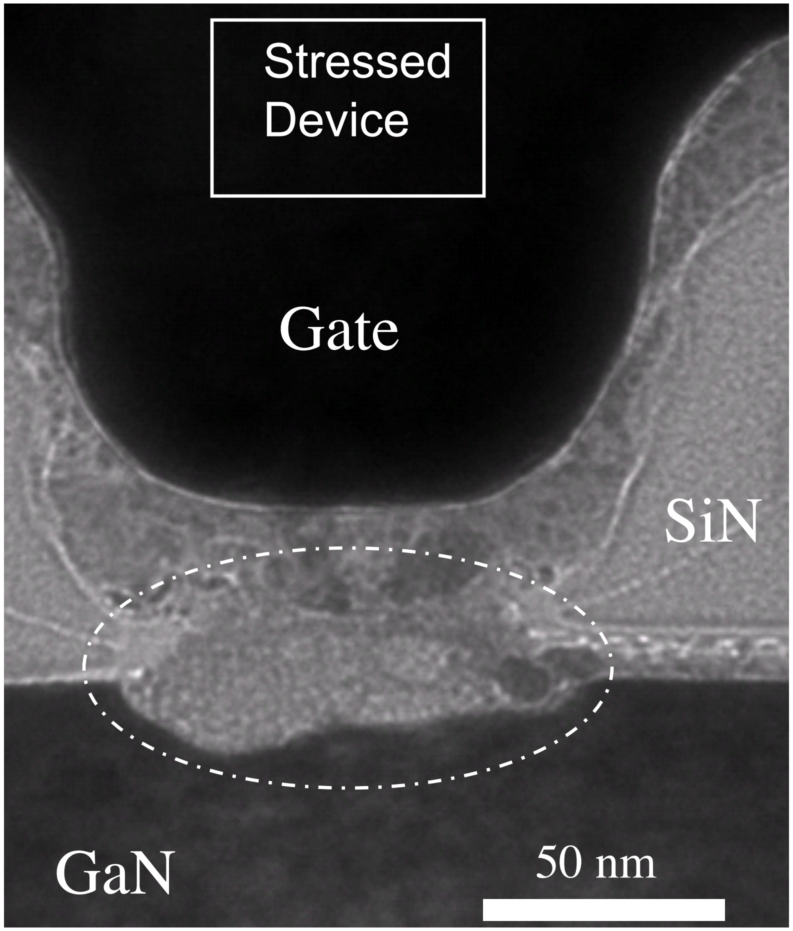
Unstressed Device



Stressed Device



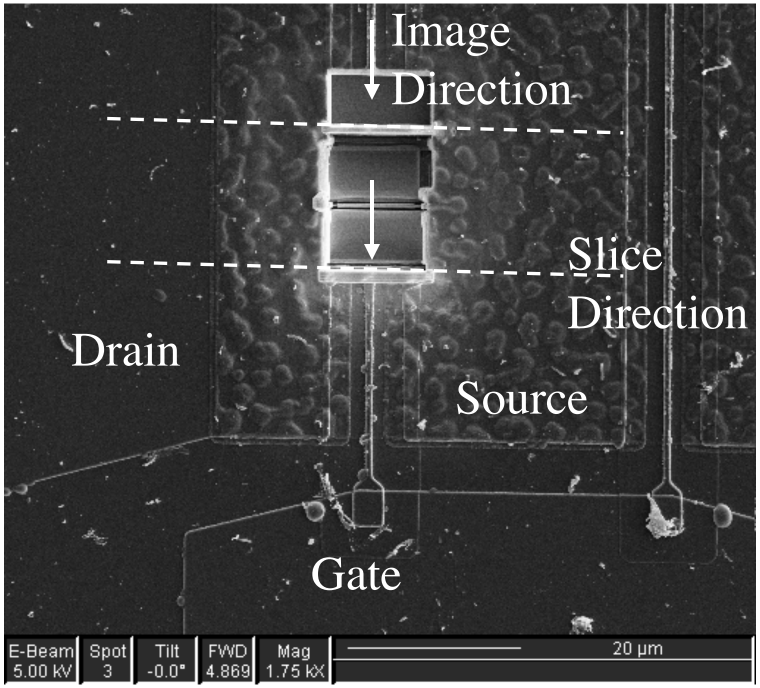
AFRL Device Study

- A combination of point and line EDS scans was performed on and near the defect region.

- Results
  - Gate defect contained a combination of materials:
    - Nickel 19 at%
    - Oxygen 35.5 at% => number is too large
    - Silicon 24.7 at%
    - Aluminum 5.4 at%
    - Gallium 15.4 at%
  - It may be a mixture between the Ni from the gate, the GaN cap, and the AlGaN epilayer
  - The Ni around the entire gate appears defective
  - LEAP analysis will be performed in order to more accurately determine the composition

AFRL Device Study

- Degradation is not present along entire gate width
- How to determine amount of degradations?
  - Develop a "slice and view" method using the FIB
    - Take a small slice of the sample using the Ga ion beam
    - Image the cross section of the slice using SEM

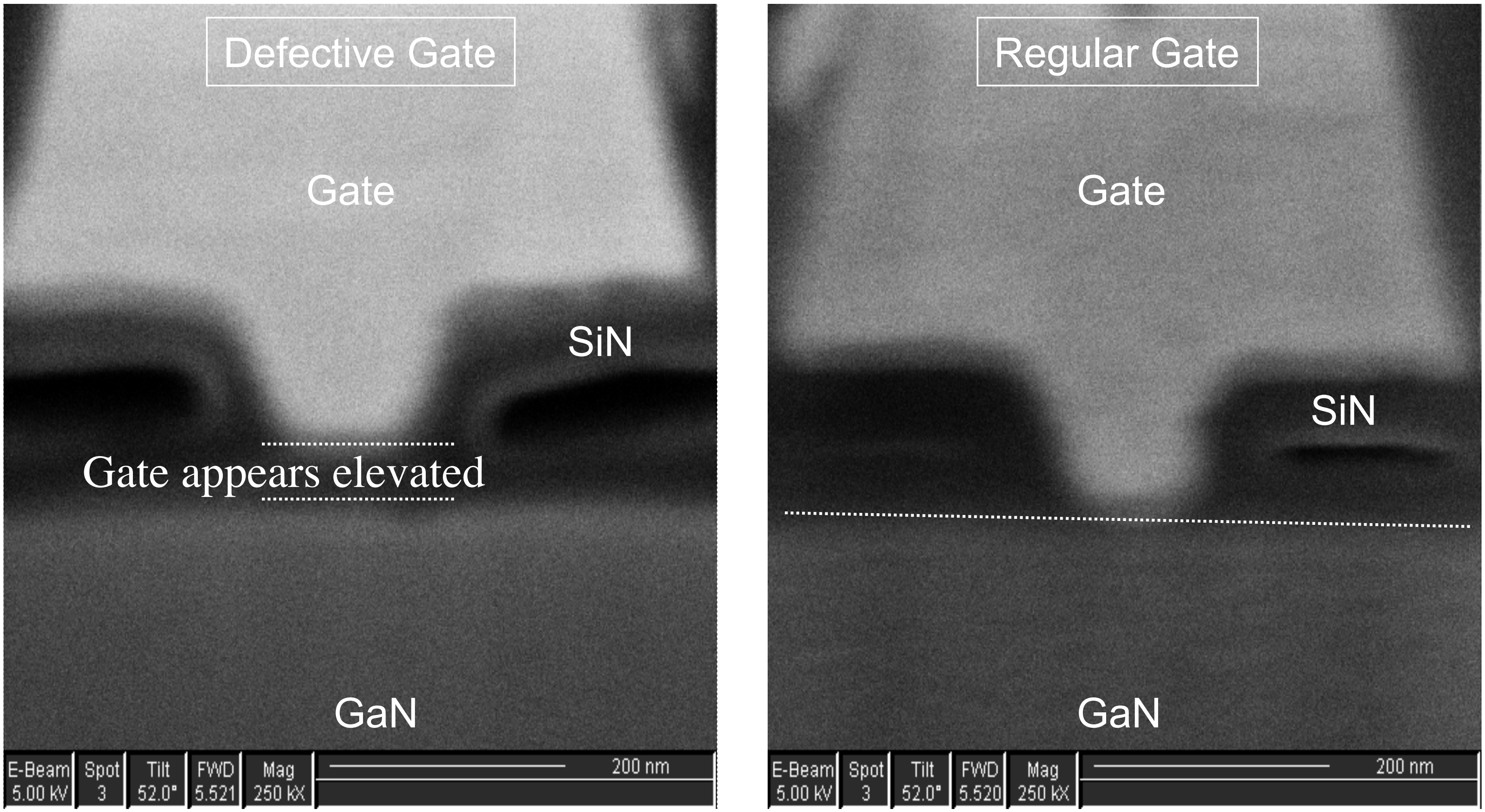


AFRL Device Study

- "Slice and View" method can be applied to the whole length of the device
  - 1 slice every 5 microns
    - Yield 20 to 30 samples per device
  - Able to quantification how far down the device the gate degradation extends
    - Correlate amount of gate degradation to device performance

AFRL Device Study

- Preliminary Results
  - Images are SEM micrographs (working to achieve better resolution)



MIT Collaboration

- We are collaborating with Prof. Jesus del Alamo at MIT
  - Group suggested the inverse piezoelectric effect for failure and have done the initial work in the area

- Providing us with unstressed and stressed devices
  - TEM
    - Image defects present (non-uniform along gate width)
  - LEAP
    - Determine the composition of the pit and crack defects

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Importance of a Zone Axis

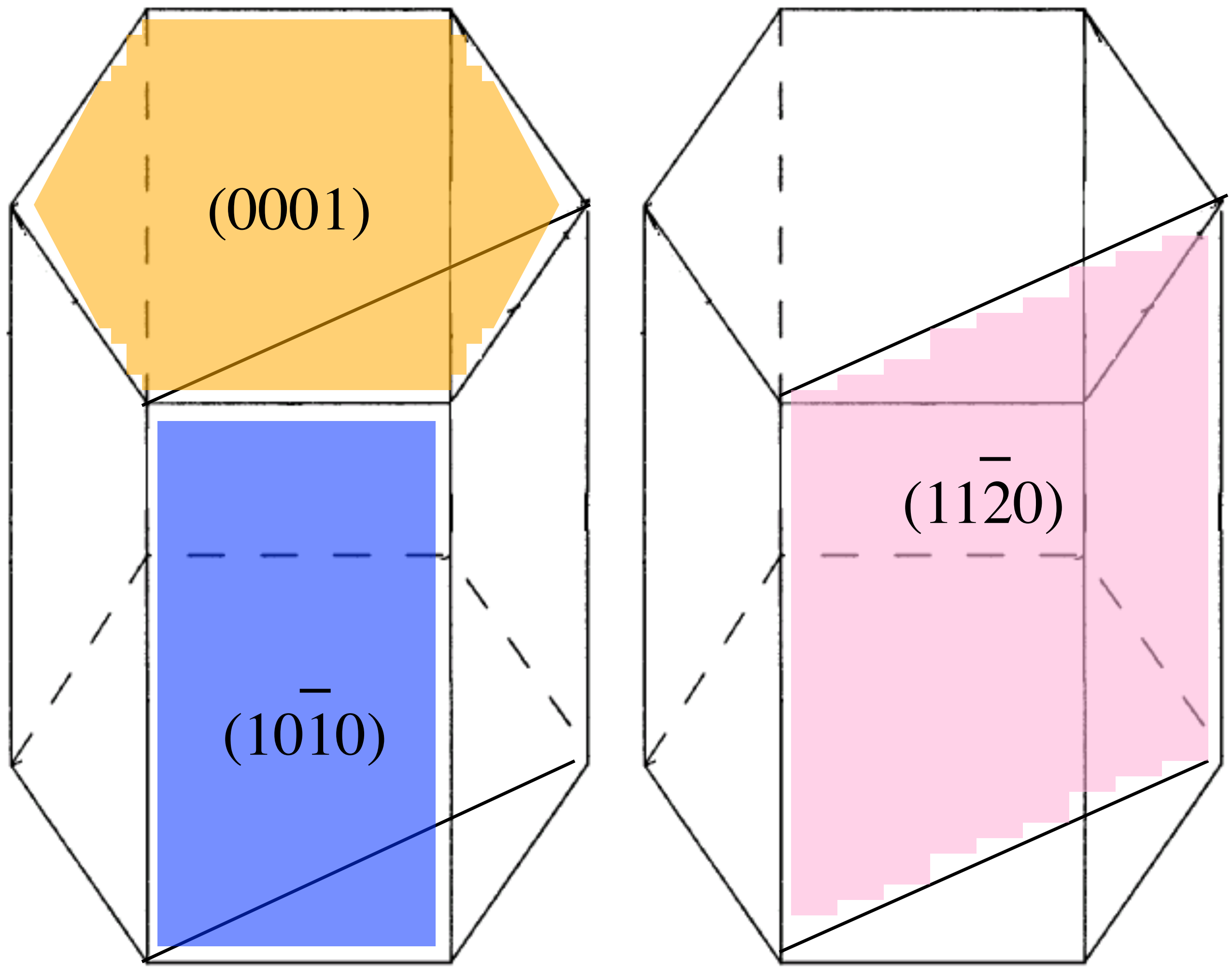
- Gates for devices on different wafer substrates from different companies are not aligned in the same crystallographic directions

- GaN's wurtzite structure makes it anisotropic
  - Different properties along different directions
    - Mechanical Properties
      - Piezoelectric coefficients
    - Electrical Properties

- Knowing the direction of gate alignment would help improve device simulation

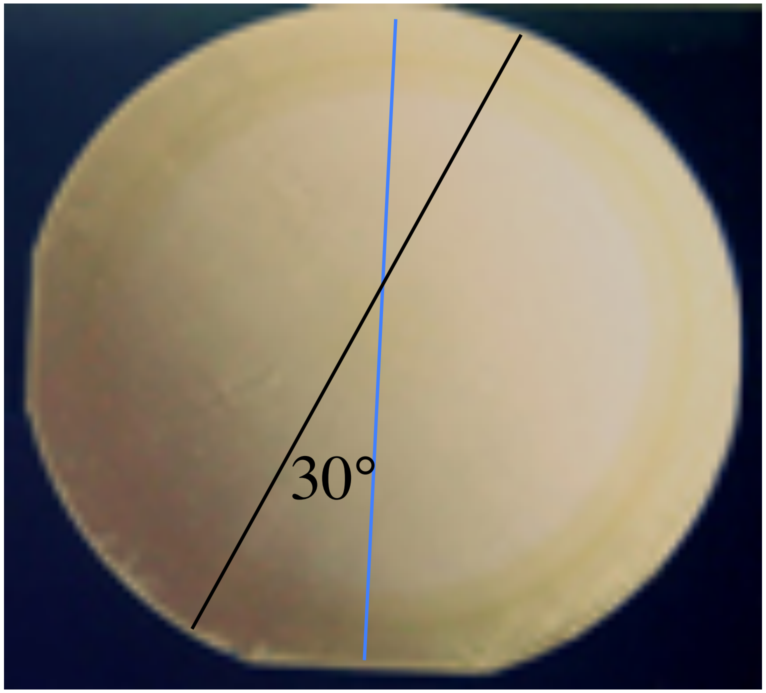
What is a Zone Axis?

- A plane of atoms
- Each prism (m) plane belongs to the {$10\bar{1}0$}
- The {$10\bar{1}0$} and {1120} planes are rotated 30^{o} from each other



Importance of the Device Zone Axis?

- Devices from different manufacturers and substrates have gates aligned to different crystallographic orientations
  - Importance: Direction affects properties
  - All Si substrate devices have been aligned to $[10\bar{1}0]$ while the SiC substrate devices are aligned to $[11\bar{2}0]$



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Bending Experiment

- Failure in devices is complicated and dependent upon many factors
  - Temperature, Electric Field, Current, Stress

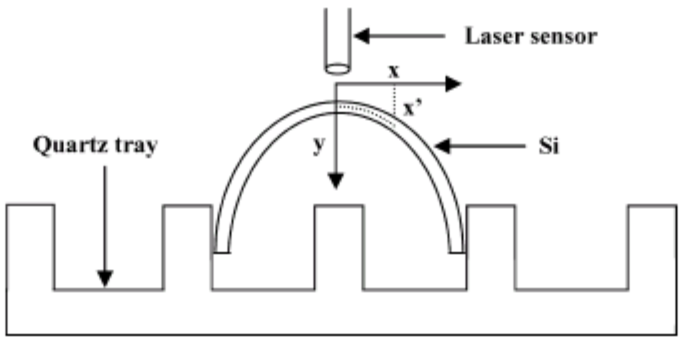
- Simplify this design by using device epi-layer wafers
  - Allows the isolation of variables
    - Stress w/ temperature for accelerated testing

- In-plane stress experiments
  - Uni-axial stress applied to Nitronex epi-structure wafers
    - Courtesy of Dr. Edwin Piner
  - Utilizes quartz bending jig
    - No applied bias or electric field and no device current
  - Ultra-thin wafer thicknesses
    - Allows higher stress states due to greater curvature

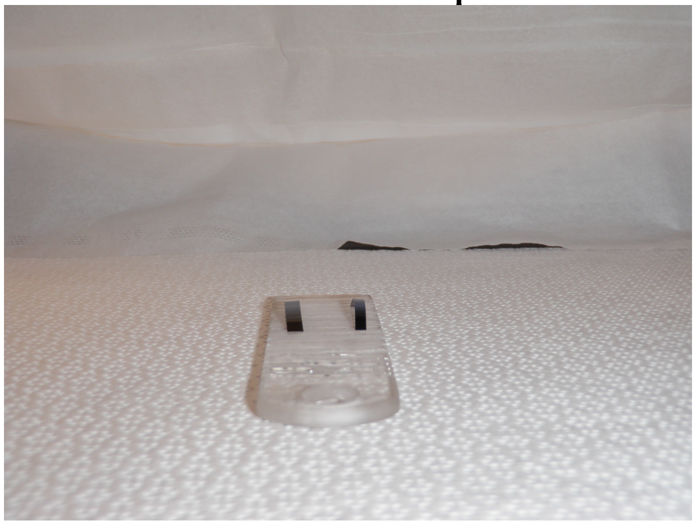
Experiment Setup

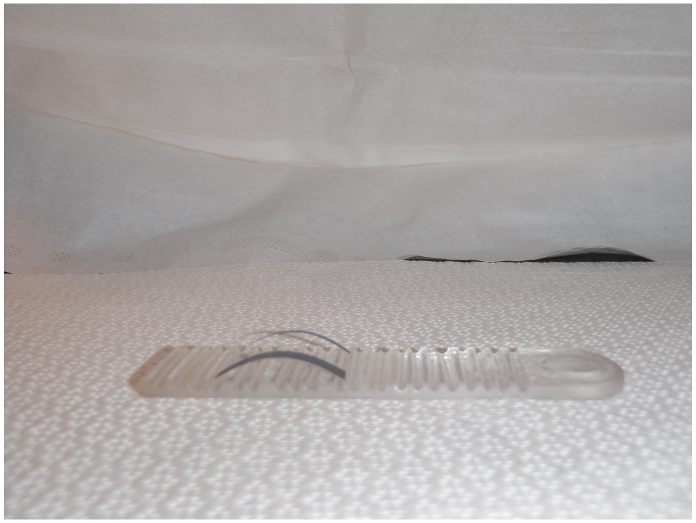
- Wafers cleaved into strips
  - 2.3mm x 25-27mm
- Strips are bent and placed into quartz tray
- Annealed in tube furnace at 450^{o}C for 25 min
  - 250 to 320^{o}C up to 1000 hr

•Ultra-thin Setup



N.G. Rudawski, et al., Materials Science and Engineering R, Vol. 61, 2008





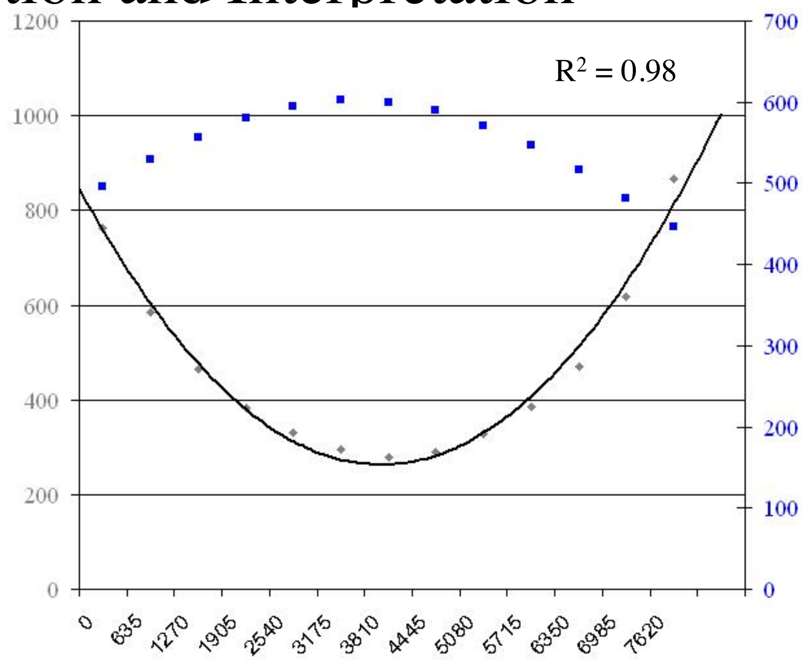
Experiment Measurement

- Strip deflection measured by laser system
  - Allows the calculation of the curvature of strip

$$\frac{1}{r(x)} = \frac{d^2y(x)/dx^2}{\left(1 + (dy(x)/dx)^2\right)^{3/2}} \qquad \sigma\,(x) = \frac{E\,c}{r(x)}$$

- Data Collection and Interpretation

Vertical Displacement (µm)

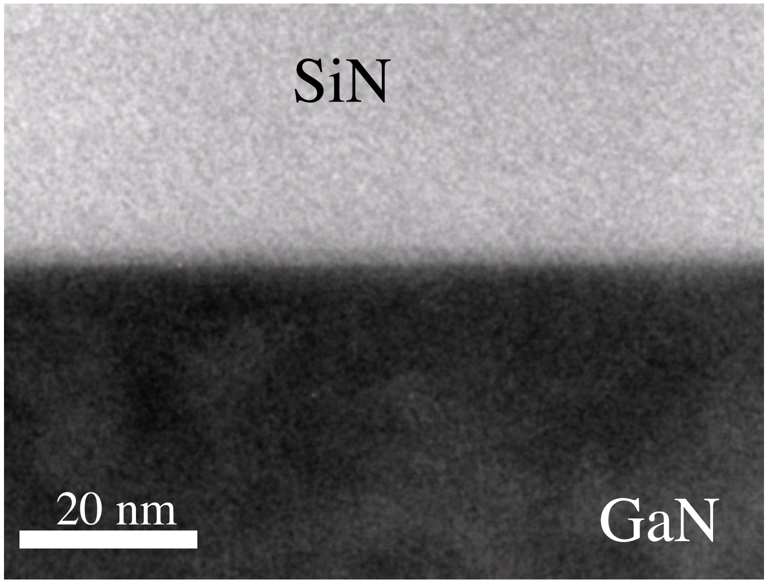


Stress (MPa)

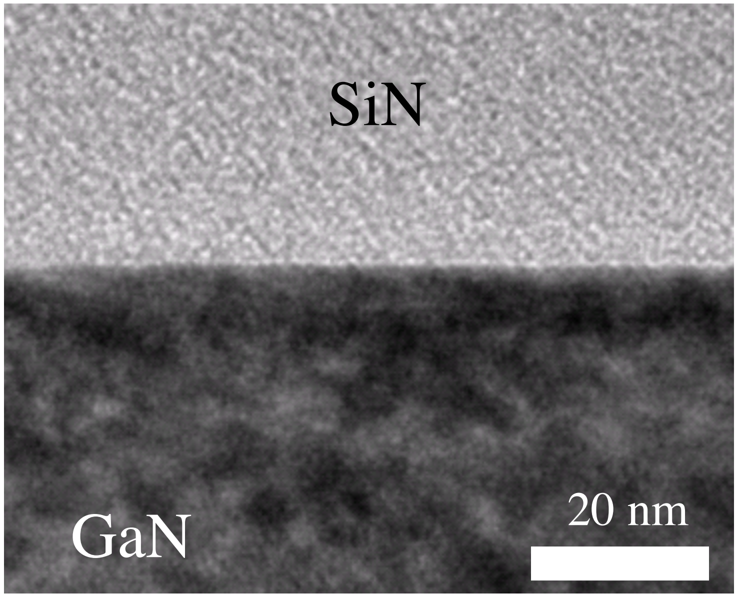
Lateral Displacement (µm)

Bending Experiment

- Preliminary Results



- As Received



- 600 MPa -Tension

- No discernible difference between the unstressed and stressed wafers

Future Work

- LEAP
  - AFRL Device Study
  - del Alamo Collaboration
- TEM
  - Devices produced within the MURI
  - Blanket wafer bending study
- Bending Experiment
  - Continue to increase stress
  - XRD
    - Changes in crystal structure
  - SIMS
    - Changes in composition
  - AFM
    - Changes in surface morphology

Conclusions

- Improved upon LEAP analysis
  - Identified M/C peak overlap issues
  - Corrected 1-D concentration profile for AlGaN epilayer
- Observed a new gate degradation in AFRL HEMTs
  - Appears to be a mixing of the gate metals and epilayers
  - LEAP analysis will be applied to achieve a more accurate composition
- Observed a difference between crystallographic directions gates are aligned to in devices
- Begun our blank wafer stress experiments
  - Achieved in-plane stresses up to 600 MPa
  - No apparent structural changes observed